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LONG-PERIOD WAVES OR SURGES IN HARBORS

By John H. Carr

HYDRAULICS DIVISION

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PAPERS

LONG-PERIOD WAVES OR SURGES IN HARBORS

By John H. Carr[1]

Synopsis

The topic of long-period waves is of importance in the design and construction of harbor facilities, since these waves affect floating objects within the confines of the harbor.

This paper reports the results of field and model studies of the sources and characteristics of long-period waves in harbors and analyzes the subjects of basin resonance and water motions induced by the waves. The particular adaptability of models to this type of study is discussed, and examples of the use of models in the design of harbor facilities are given.

Long-period waves are known to affect the motion of moored ships, and a discussion of this phenomenon is given.

Introduction

Long-period waves are of importance in harbor operations because of the effect of their associated water motions on floating objects. Like all other waves, long-period waves are characterized by oscillatory horizontal and vertical water motions, and these motions cause all floating objects to oscillate at the wave frequency and with amplitudes comparable to the water motion amplitude, unless the objects are restrained. However, for waves of the same height, the horizontal amplitude of the water motion increases linearly with the wave period. Thus long-period waves of relatively low wave height can induce greater amplitude motions of a nonrigidly moored ship than those induced by high storm waves of the usual 8- to 15-sec periods.

The Hydraulic Structures Laboratory of the California Institute of Technology, at Pasadena, has conducted investigations of long-period wave disturbances in connection with two studies made for the Bureau of Yards and Docks, United States Department of the Navy. This paper utilizes three of the topics of those investigations:

Note.—Written comments are invited for publication; the last discussion should be submitted by **October 1, 1952.**

[1] Senior Research Engr., Hydrodynamics Laboratory, California Inst. of Technology, Pasadena, Calif.

1. A review of the characteristics of long-period waves in harbors, including an analysis of the phenomena of basin resonance, an analysis of the wave-induced water motions, and some postulations concerning the sources of long-period waves;

2. A discussion of the particular usefulness of model studies for the solution of problems of harbor design arising from long-period wave phenomena; and

3. A discussion of an important engineering problem associated with long-period wave disturbances, namely, the motion of moored ships under the influence of this type of excitation.

Characteristics of Long-Period Waves in Basins

Standing Wave Pattern.—An important factor affecting long-period wave motion in harbors is the possibility of these long-period waves exciting an oscillation of the harbor basin, with resulting build-up of wave height (hence water motion) as a result of resonant amplification, in a manner analogous to a mechanical vibrating system.

The oscillation of a basin is a special case of a standing wave pattern and is best considered in that light. When a wave train encounters a reflecting shore line, the reflected wave passes through and interferes with the oncoming one. The effect of this interference is reinforcement where incident and reflected motions coincide and cancellation where the motions are opposed. Since the lengths of the incident and reflected wave lengths are the same, the points of reinforcement and cancellation are fixed in space; and a standing wave pattern, with stationary positions of maximum and minimum motion, or loops and nodes, is produced. For the special case in which the direction of incident wave travel is normal to a straight reflecting surface, the standing wave pattern will take the form of a series of straight crests and troughs parallel

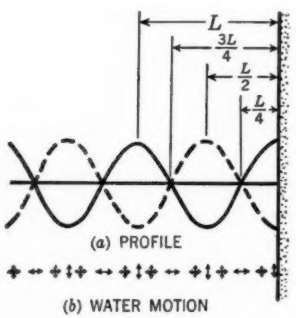


Fig. 1.—Standing Waves

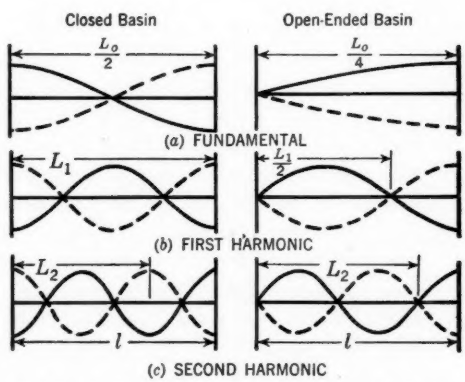


Fig. 2.—Surface Profiles for Oscillating Waves

to the shore, as shown in Fig. 1. The vertical motion in this case is a maximum at the reflecting surface and at 1/2, 1, 3/2, 2, and so on, wave lengths offshore (or at integer multiples of half the wave length offshore) and zero at distances of 1/4, 3/4, 5/4, and so on, wave lengths offshore. The horizontal motion is

zero at the boundary and at the other loop positions and a maximum at the nodal positions.

These results may be derived simply in analytical form as follows: The profile of the incident and reflected wave trains may be expressed in terms of their vertical amplitudes, η_1 and η_2, and of the two variables of time (t) and horizontal distance (x). The equations expressing this relationship are:

$$\eta_1 = a \sin 2\pi \left(\frac{t}{T} - \frac{x}{L}\right) \qquad (1a)$$

$$\eta_2 = a \sin 2\pi \left(\frac{t}{T} + \frac{x}{L}\right) \qquad (1b)$$

in which a is the maximum wave amplitude; T is the wave period; and L is the wave length. The resultant water surface profile is given by the sum of η_1 and η_2, or

$$\eta_1 + \eta_2 = 2\,a \sin 2\pi \frac{t}{T} \cos 2\pi \frac{x}{L} \qquad (2)$$

from which the values of $\frac{x}{L}$ listed previously for maximum and zero vertical motion may be readily verified.

If a second reflecting boundary occurs at a loop position, the basin so bounded constitutes a system capable of executing free vibrations, or oscillation. In the absence of damping, the standing wave pattern or its equivalent, a progressive wave travelling back and forth between the boundaries will persist with the initial amplitude. If energy losses do occur, as in any actual physical system, the basin oscillation is a typical damped free vibration, and the wave amplitude decreases exponentially with time. If, instead of only an initial excitation, the harbor is subject to a periodic addition of energy at the fundamental or at some harmonic period of free oscillation of the basin, resonance will occur. The motion will build up in amplitude until the corresponding higher rate of friction loss balances the energy added per cycle and will then remain at this steady-state level as long as the excitation persists. This resonant oscillation is a special case of forced oscillation, which, in general, is an oscillation at a period determined by the period of the excitation instead of by the natural period of the basin. Thus, whenever long-period waves enter a harbor, the harbor basin is essentially undergoing forced oscillation at the imposed wave periods; and as the period of forced oscillation approaches the fundamental or a harmonic period of free oscillation of the basin, the amplitude of the motion within the basin will increase, reaching a maximum at resonance, when the two periods coincide.

The fundamental mode of oscillation of a basin is represented by the case in which the second reflecting boundary occurs at the first loop offshore, or in which the distance between reflecting surfaces is one-half wave length. The first, second, and subsequent harmonics correspond to successive loop positions, or to basin lengths of 1, $1\frac{1}{2}$, 2, and so on, wave lengths and subsequent integer multiples of half the wave length as shown in Fig. 2(a). The fundamental period (T_o) of the oscillation is, therefore, the period of a wave whose length

is twice the distance between reflecting boundaries. The harmonic period corresponding to the harmonic modes of oscillation are 1/2, 1/3, 1/4, and so on, of the fundamental, or

$$T_n = \frac{2\,l}{(n+1)\,C} \qquad (3)$$

in which n is the order (1st, 2nd, and so on) of the harmonic, $n = o$ corresponding to the fundamental period, C is the wave velocity, and l is the distance between boundaries.

A second type of basin oscillation is possible if, instead of a reflecting surface located at a loop, an opening across which flow may occur is located at a node and connects the basin to a relatively large body of water. The fundamental mode of oscillation for such a configuration is that for the case of the opening at the first node position (or 1/4-wave length offshore). Harmonic modes are represented by the location of the opening at successive nodal positions as shown in Fig. 2(*b*). Except for the shape of the water surface, the oscillation proceeds in the same manner as previously discussed, and it is readily apparent that the periods of the oscillation are given by

$$T_n = \frac{4\,l}{(n+1)\,C} \qquad (4)$$

The application of these equations to the computation of the natural periods of oscillation of a harbor is simplified by the fact that the long-period waves considered are always shallow-water waves in typical harbor-water depths. Hence, their velocity is given by

$$C = \sqrt{g\,d} \qquad (5)$$

in which d is the water depth. The average value of C and the length l between oppositely disposed reflecting surfaces, or reflecting surface and opening, can be computed readily from harbor charts and a close approximation of the natural periods thus arrived at.

It may be noted that the apparent damping is much higher for the higher harmonics of basin oscillation than for the fundamental, so much so that basin oscillation at higher than the second or third harmonic is seldom observed. This is not because of the friction losses associated with the water motion, since this energy loss is independent of wave period, but is caused by the loss of energy by imperfect reflection at the basin boundaries. The quality of a reflecting surface is a function of the magnitude of its irregularities with respect to the wave length reflected. Thus, the same stretch of shore line may be a very good reflector for the long wave lengths of the fundamental mode of oscillation and a rather poor reflector, scattering a large part of the imposed energy out of the path of oscillation, for the shorter wave lengths of the higher harmonics.

As a final word on the theoretical aspects of basin oscillation, it may be remarked that in a typical harbor basin there may be several possible modes of oscillation. If the fundamental or harmonic periods of two or more of these modes are the same, both modes will be excited by an exciting wave of this

period. In this case, the energy of the forcing wave is split between the two modes of oscillation and their resulting amplitudes will be less than when excited separately.

Water Motion.—The motion of the water in the long-period, shallow-water waves considered in this paper is very closely represented by the classical wave theory of G. B. Airy.[2] The particles may be considered to be travelling in elliptical orbits whose horizontal major diameter is nearly of constant magnitude from the surface to the bottom and whose vertical minor diameter varies linearly from a maximum at the surface (where it is equal to the wave height in magnitude) to zero at the bottom. The magnitude of the horizontal diameter is a function of the wave length or period, the wave height, and the water depth; and it is very much larger than the surface value of the vertical diameter.

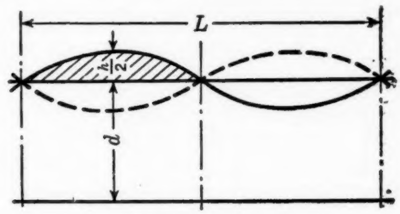


FIG. 3.—HORIZONTAL VELOCITY

The horizontal water particle velocities may be calculated by assuming a sinusoidal wave profile and considering the flow across nodal sections as the wave form progresses (Fig. 3). The volume of water (V_w) that must flow across nodal sections is

$$V_w = \int_o^{L/2} \frac{h}{2} \sin \frac{2\pi x}{L} \, d x = \frac{h L}{2 \pi} \quad \text{(6)}$$

in which h is the vertical height of the wave. Hence, the average flow rate (Q) across the nodal section in one half the wave period is

$$Q = \frac{V_w}{\frac{T}{2}} = \frac{h L}{\pi T} \quad \text{(7)}$$

The average horizontal velocity across the nodal section is, therefore,

$$V_{av} = \frac{Q}{A} = \frac{h L}{\pi d T} \quad \text{(8)}$$

in which V is the horizontal velocity and A is the cross-sectional area. The amplitude of a water particle will be

$$a = V \frac{T}{2} = \frac{h L}{2 \pi d} \quad \text{(9)}$$

Since $\frac{L}{T} = C$, and $C = \sqrt{g\,d}$ for these shallow-water waves,

$$V_{av} = \frac{\sqrt{g}}{\pi} \frac{h}{\sqrt{d}} \quad \text{(10)}$$

The maximum horizontal velocity, being $\frac{\pi}{2}$ times the average velocity for

[2] "A Summary of the Theory of Oscillatory Waves," by Morrough P. O'Brien, *Technical Report No. 2*, Beach Erosion Board, Corps of Engrs., U. S. Dept. of the Army, Washington, D. C., 1942.

sinusoidal motion, is

$$V_{max} = \frac{\sqrt{g}}{2} \frac{h}{\sqrt{d}} \qquad (11)$$

Thus the horizontal water velocities associated with long-period wave motion are independent of wave period or length but are directly proportional to the wave height and inversely proportional to the square root of the water depth. This latter factor is of special interest since it indicates that shallow areas of a harbor will be more active than deeper regions under the same wave conditions.

To translate these equations into numerical values of water particle amplitude and velocity that may be experienced in typical harbors during typical surge conditions, it is necessary to estimate the height of the imposed waves. The amplitudes of long-period waves in the ocean are very small compared to ordinary wind waves, usually being considerably less than 1 ft in height. For example, the largest amplitude long-period waves recorded at Terminal Island, Los Angeles, Calif.,[3] were those due to the Alaskan earthquake of April 1, 1946, and on this occasion 12-min period wave trains 1 ft in height and 6-min period wave trains ½ ft in height were measured at the outer breakwater. With a resonant amplification factor between 1 and 2, which appears to be an average range for typical harbors, such a strong surge might produce a vertical water motion of 1 ft inside the harbor. The resulting average horizontal velocity would be 0.266 ft per sec at a nodal section in a harbor with 45-ft water depth and the corresponding displacement of the water particles would be 0.133 times the wave period in seconds, or 48 ft, for example, if this period were 6 min. At the other extreme, a low surge of 3-min period and 0.2 ft height would produce average horizontal velocities of 0.053 ft per sec with horizontal displacements of nearly 5 ft.

It should be emphasized that, since large amplitude surge motion will usually be the result of resonant amplification, the water motions are the result of a standing wave pattern and the vertical motion is a maximum at the loops, as at the reflecting boundaries, although the horizontal motion is zero there. Conversely, the vertical motion is zero, and the horizontal motion is a maximum at nodal positions, such as ¼-wave length offshore of the reflecting boundary. Thus, there are alternate active and quiet zones in the harbor, their size and distribution being a function of the period of oscillation of the harbor.

Sources of Long-Period Disturbances.—Although the presence of long-period waves in harbors have occasionally been ascribed to local phenomena such as earthquakes, local winds, and atmospheric pressure anomalies, it is fairly certain that in practically all cases the source of the disturbance is a long-period wave train arriving from the open sea.

One clearly recognized source of such waves are seismic disturbances, an example of which was the Alaskan earthquake of April 1, 1946.[3] Waves caused by this disturbance were observed along nearly the entire western coast of

[3] "Memorandum on Waves in the Los Angeles Harbor Associated with the Alaskan Earthquake of April 1, 1946," by Robert T. Knapp and Robert E. Carr, Report to the Bureau of Yards and Docks (Contract No. y-13116), U. S. Dept. of the Navy, Washington, D. C., April, 1947.

North and South America, and persisted for approximately 24 hr. In the southern California region this disturbance included a wave period spectrum of from 1 to 60 min, with 6- and 12-min period waves predominating. Fig. 4 is a reproduction of a marigram from a tide gage station in Los Angeles outer harbor for this occasion.

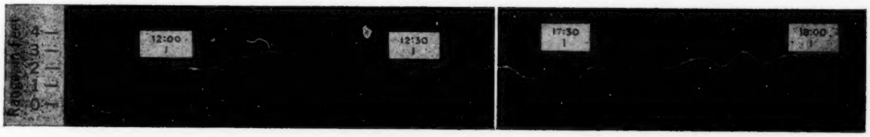


FIG. 4.—MARIGRAM RECORD OF LONG-PERIOD WAVES IN LOS ANGELES (CALIF.) HARBOR

The infrequency of large-scale submarine earthquakes indicates that some other mechanism of long-period wave generation must be responsible for the relatively frequent occurrences of harbor surging. An attractive hypothesis of such a mechanism is contained in the theory of surf beats. The theory of beats in the case of the superimposing of two waves of nearly the same period is well known, especially in acoustics. The familiar result is a wave form consisting of a long-period modulation of the short-period interfering elements as shown in Fig. 5. For the case of interference of water wave trains in an ocean basin, the result is a water surface profile that may appear to be the superposition of long- and short-period components, but, in fact, is not. Although this process produces a long-period vertical water motion, the really important factor of long-period horizontal water motion is lacking, since there is no actual long-period component present in the wave system.

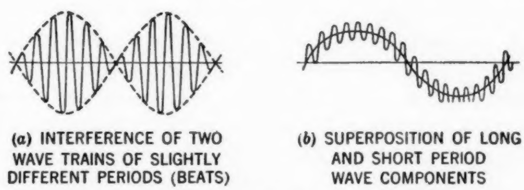


FIG. 5.—WATER SURFACE PROFILES

However, theoretical and experimental evidence[4] indicates that, in the presence of the nonlinear boundary conditions of the surf zone, the effect of the inherent variability of wave trains (with respect to period, and especially with respect to height) is to produce a true long-period wave train. Thus, it is estimated that beaches may reflect approximately 1% of the energy incident on them in the form of long-period waves. This phenomenon has been repeatedly observed in small bays and coves along the California and Oregon coasts, where it has been interpreted as the local cause of local surging. The reporters of these observations have tended to discount the theory of the existence of long-period wave trains as a general condition throughout large ocean areas.

Evidence that the latter theory is an important aspect of the long-period wave picture is given by the several years of observations at Terminal Island[5]

[4] "Surf Beats," by W. H. Munk, *Transactions*, Am. Geophysical Union, Vol. 30, 1949, p. 849.

[5] "Wave and Surge Study for the Naval Operating Base, Terminal Island, California," *Hydrodynamics Laboratory Publication No. 55*, California Inst. of Technology, Pasadena, Calif., 1945.

where on many occasions the most severe surging conditions corresponded to an otherwise calm sea. This is a condition not compatible with the local surf beat. Further evidence has been obtained in the form of simultaneous tide gage records (marigrams) from San Diego, San Pedro, Catalina Island, and Port Hueneme, Calif., showing identical long-period wave activity at these locations. Since these locations span a 200-mile stretch of the southern California coastline, such records are convincing evidence that long-period wave trains do exist from time to time as a general ocean condition and that the search for the source of excitation for harbor surging cannot be confined to local phenomenon. Therefore, it is suggested that, in general, long-period waves are due to surf beat, but surf beat occurring at some distant part of an oceanic basin instead of in the immediate vicinity of the observing station.

Model Studies

The Hydraulic Structures Laboratory has had the opportunity of investigating long-period wave phenomena in harbors in connection with two research contracts with the Bureau of Yards and Docks. Each of these contracts has involved both field and model studies, and together they have served to illustrate the importance of long-period waves in harbor design and the utility of model studies in the solution of such problems.

Reasons for Model Studies.—The principal reason for the usefulness of model studies in harbor design is that, whereas the amount of energy entering the harbor can be accurately calculated for a given wave height and direction if the breakwater gate alinement is fixed, the energy level inside the harbor is a function of these known factors plus the unknown factors of basin configuration and damping capacity. Since the frictional damping loss which must equal the rate of energy input in the steady-state condition increases with increasing energy level, a harbor acts as an energy reservoir, storing up wave energy until a level is reached at which the rate of energy loss balances the input. The factors that determine the damping capacity of a harbor are not only difficult to evaluate by analytical methods, but in a typical harbor design study it may be necessary to consider the effect of a number of possible development plans, each of which imply a change in the basin damping capacity. Since the factors that affect the damping capacity may be accurately reproduced in a properly designed model, such a model is more than an empirical testing device. It may be likened to a computing machine into which a large number of variables can be introduced and by which the net result of these variables can be given in a form suitable for use in engineering design.

For the particular case of long-period wave disturbances, the resultant water motion in particular areas within a basin is the result of the sum of incident and reflected waves. Since the standing wave pattern is determined by the configuration of the reflecting boundaries, the harbor shape will have an important bearing on the water motion within the basin. The particular utility of model studies in such problems is caused by the fact that in actual harbors there are a multiplicity of reflecting surfaces, each of which is responsible for a different standing wave pattern for each imposed wave period. Hence, it is a practical impossibility to compute the net effect in a particular

area. A model, however, gives the integrated effect of all of these standing wave patterns at each point.

Examples of Model Studies.—Brief descriptions of the model studies conducted under the research program mentioned above are given in the following sections.

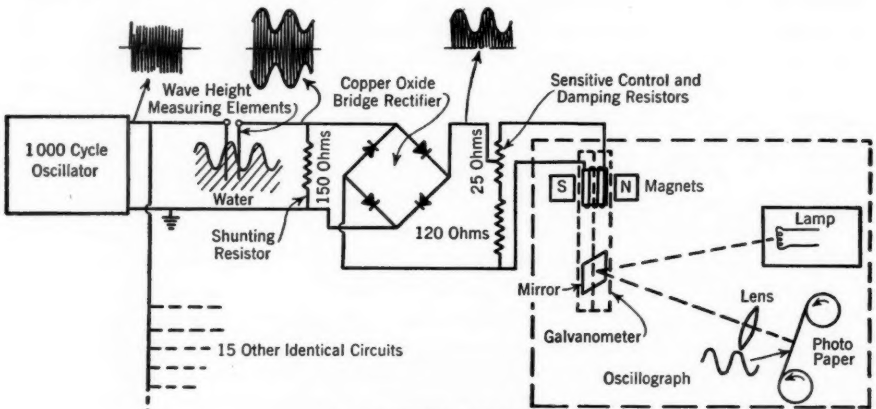
Terminal Island.—The first of the model studies was in connection with harbor improvements at the Naval Operating Base (NOB), Terminal Island. The presence of long-period waves in the ocean regions adjacent to southern California have long been known; the surge conditions in Los Angeles harbor, in particular, were noted in the *United States Coast Pilot* since 1914. The very low level of pre WORLD WAR II harbor activity accounted for the fact that this condition was largely ignored. With the tremendously increased wartime activities, the surge problem became more serious, and steps for its alleviation in the NOB area were taken. A proposed solution—the construction of an impervious mole to protect the area—was accordingly initiated, and at the same time (December, 1943) the Hydraulic Structures Laboratory was requested to study the problem and to assist in the mole design.

In the first stage of the study, efforts were made to determine the nature of the damaging ship motions and of any correlation between ship motion and observable water motions. These investigations indicated that during periods of damage the longitudinal and transverse ship motions were of high amplitude and long period (on the order of 4 to 10 ft and 2 to 3 min), whereas the vertical ship motion was of short period (10 to 15 sec), corresponding to the period of the prevailing wind waves. Modified tide gages were established in the NOB area, and from these it was determined that during periods of damage, low amplitude waves with periods corresponding to the long-period ship motion were present.

The Los Angeles harbor outer breakwater, which forms the primary protective barrier for the NOB area, contains two gates approximately 2,000 ft wide, and terminates about $2\frac{1}{2}$ miles offshore at its eastern end, leaving the east side of the harbor area unprotected. These openings provide a direct path for wave energy to enter the harbor; and, in addition, field studies showed the outer breakwater to be sufficiently porous to admit a small fraction of the typical short-period wind waves into the harbor. Since the breakwater is even more "transparent" for long-period waves than it is for short, it is apparent that such long-period motion can enter the harbor area from any direction, with the most severe conditions being those in which the waves are directed through one of the gaps in the breakwater. These field studies verified the existence of long-period waves in the NOB area and demonstrated the relationship between the ship surging and these waves. These conclusions served to define the requirements of the proposed mole; that is, to eliminate as much as possible of both the short- and long-period wave motion and insofar as possible to define a basin whose natural periods would not be in the range of probable exciting wave periods.

The orientation of the mole gate was fixed by the necessity that it be centered on the existing dredged ship channel. The approximate over-all dimensions of the mole basin were fixed by minimum basin area requirements and

funds available. Proceeding within the framework of these limitations, the model study investigated the nature of the water surface disturbances within the basin for 14 mole configurations. The comparison of effectiveness of the various role configurations was based on the measured wave disturbances in the vicinity of the dry docks and piers, since this area had been defined by NOB authorities as the critical area that was to receive the best possible protection. This study considered the effect of both 15-sec period wind waves and 2-, 3-, and 4-min surges.



(a) SCHEMATIC DIAGRAM

(b) CONDUCTIVITY ELEMENTS

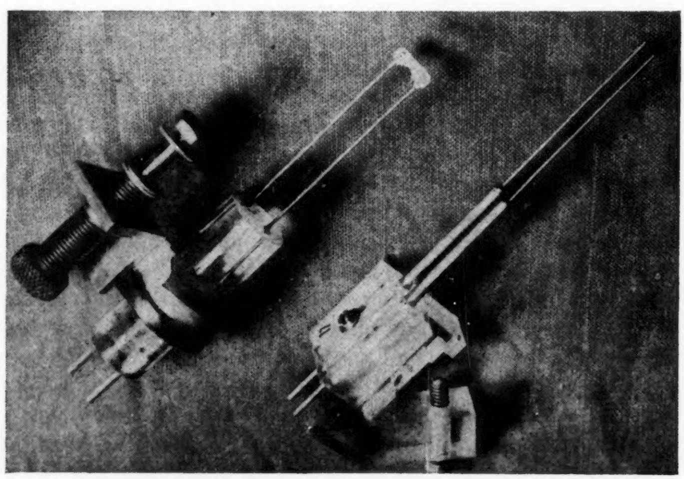


Fig. 6.—Laboratory Wave Height Measuring System

Wave heights were measured by electrical conductivity elements, consisting of a pair of spaced wires projecting into the water. A constant alternating voltage is applied across the two wires of an element. The resulting current flow depends on the immersion of the element and hence is a function of the wave height at any instant. The current signal, representative of the vertical

water motion at the element location, is recorded on a galvanometer oscillograph (Fig. 6).

This study fixed the choice of the optimum mole alinement, and further studies were made to completely determine the water motion in the mole basin so defined. A frequency response study, in which the maximum vertical water motion anywhere within the basin was plotted against imposed wave period, was carried out for a range of wave periods from 10 sec to 15 min (Fig. 7).

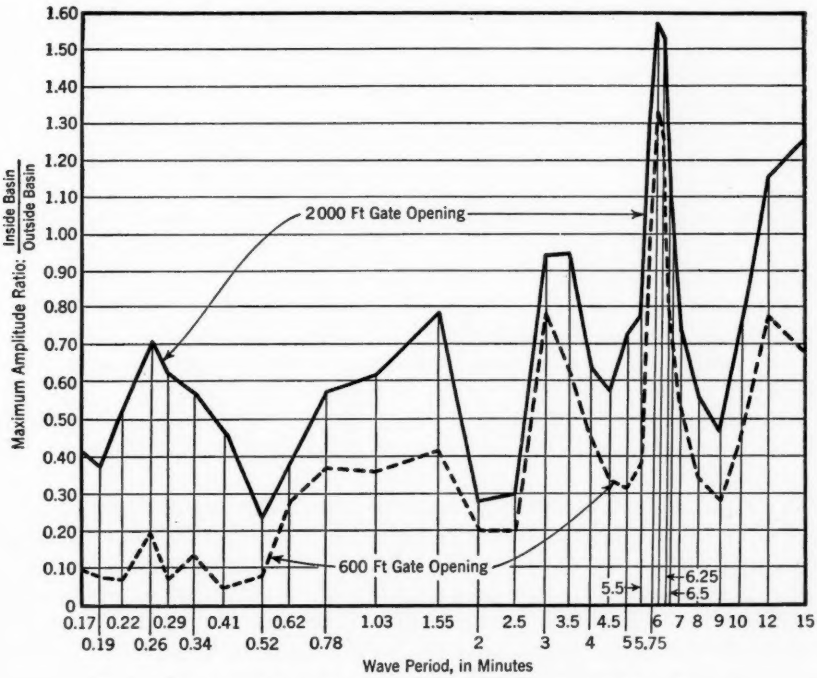


FIG. 7.—FREQUENCY RESPONSE ANALYSIS FOR TERMINAL ISLAND MOLE BASIN

The largest response was obtained with a period of 6 min, and lesser peaks in the response curve occurred at 12, 3, and $1\frac{1}{2}$ min, with practically uniform response in the 10- to 20-sec period range of the usual imposed ocean waves. The basin mode corresponding to the 6-min peak is a longitudinal oscillation with in-phase loops at opposite ends of the basin and an opposite-phase loop at the center of the basin. This is, therefore, the first harmonic of the longitudinal basin oscillation and is of higher amplitude than the 12-min fundamental of this mode because the mole entrance is near the center of the longitudinal dimension of the basin. The entering wave spreads out as it passes through the gate and starts a wave crest travelling towards each end of the basin, thus exciting the symmetrical first harmonic of the longitudinal mode. A 12-min wave also spreads and sends disturbances travelling toward each end of the basin, but since the mode of oscillation for the 12-min fundamental is antisymmetrical, this oscillation is not as strongly excited. The 3-min oscillation

is composed of several modes, the most prominent being the fundamental of a path across the width of the basin, with the third harmonic of the longitudinal mode being excited also. Since the pattern is more complicated and the incoming energy more subdivided, the maximum amplitudes are lower than those for the 6-min period. This same reason explains the continual reduction in observed amplitudes at still lower periods, the number of possible modes becoming increasingly large and the amplitudes correspondingly lower.

Further studies were made to determine the contours of vertical water surface disturbance throughout the mole basin for various wave and surge periods. Such measurements served to delineate the characteristic modes of oscillation of the basin and established the regions of maximum and minimum motion in the mole basin.

Apra Harbor, Guam, Marianne Islands.—The second study in which the Hydraulic Structures Laboratory has investigated long-period waves was a model investigation of Apra Harbor.[6] In this case there were no field data available dealing with long-period waves in the vicinity, since shipping activities were practically nil until the harbor's development by the United States Navy in the closing phases of World War II.

Because the potential importance of long-period waves was realized as a result of the Terminal Island studies, part of the program of field measurements was devoted to the investigation of the inclusion of long-period components in the wave trains in the ocean areas surrounding Apra Harbor. Laboratory measurements were made with a harbor model to determine the possible modes of oscillation within the harbor and the resulting horizontal and vertical water motions.

The field measurements were made with specially modified recording tide gages, the float-well orifices being proportioned to exclude the obscuring effects of normal surface waves, but to permit the recording of waves with periods longer than 1 min. The recording speed was increased to 30 in. per hr to give good time resolution of the shortest effective wave. Five of these gages were installed, three in the harbor and two in the adjacent ocean areas, and were operated for a period of several months. During this time no evidence of persistent trains of long-period waves of the type found in the Terminal Island study were observed, only very long-period, low amplitude wave trains with periods of about 45 and 90 min being recorded. Although this is a somewhat sterile result, it may be remarked that it does not furnish conclusive evidence that the Apra Harbor area is never visited by waves in the period range from 1 to 6 min, since the observations at Terminal Island indicate that the frequency of occurrence of such wave trains is very irregular and long intervals may elapse between successive strong surge conditions. The measurements at Apra Harbor were necessarily of limited duration because of schedules and funds.

Apra Harbor is an even more complicated basin than the NOB mole basin at Terminal Island, and the number of possible paths or modes of oscillation is therefore greater. In spite of this complication, an effort was made

[6] "Model Studies of Apra Harbor, Guam, M. I.," *Hydrodynamics Laboratory Report No. N-63*, California Inst. of Technology, Pasadena, Calif., 1949.

to predict the modes and periods of resonant oscillation of the harbor; subsequent model experiments showed that this could be done with fair success, as evidenced by Table 1. For the Apra Harbor study, the frequency response

TABLE 1.—PREDICTED AND OBSERVED MODES OF APRA HARBOR OSCILLATION (WAVE PERIOD OF GUAM, IN MINUTES)

Mode number	Direction[a]	Location	Predicted			Observed				
			Fundamental	Harmonic		Fundamental	Harmonic			
				1st	2nd		1st	2nd	3rd	4th
1	E-W	Basin[b] to open harbor entrance[c]	29.0	9.5	5.8	31.5[d]	10.5	6.5	4.6	3.6
1?	E-W	Basin[b] to breakwater near entrance	12.5	6.3	4.2	...	...	...	...	...
2	E-W	LST landing[e] to harbor entrance[c]	...	...	...	20.0[d]	6.7	4.0	2.9	...
3	E-W	Inner breakwater[f] to harbor entrance[c]	15.0	5.0	3.0	15.0[d]	5.0	3.0	...	...
3?	E-W	Breakwater[f] near harbor entrance	6.5	3.2	2.2	...	...	...	...	...
4	N-S	Gab-Gab Beach to outer breakwater	4.4	2.2	1.4	4.4[d]	2.2	1.5[d]	1.1	...
5	E-W	Basin[b] to inner breakwater[f]	5.8	2.9	1.9	5.7	2.9	1.9	...	...
6	N-S	In repair basin	3.2	1.6	1.1	3.8	1.9	1.3	...	...
7	N-S	South end to Dock N-1[g]	6.9	3.4	2.3	6.4	...	...	...	...
8	NE-SW	Dry dock to Dock W-1[g]	...	...	...	5.0	...	...	...	...
9	NW-SE	Dock Z-1 to southeast shore[g]	...	...	...	3.8	1.9	...	...	...
10	E-W	Dry dock to Dock Y[g]	...	...	...	3.8	1.9	...	...	...
11	E-W	Dry dock to Dock Q[g] [h]	4.5	2.2	1.5	4.4	2.2	...	...	...

[a] The letters N, E, W, and S denote "north," "east," "west," and "south," respectively. [b] East end of repair basin. [c] Open harbor entrance, Mode 2 with an inner breakwater and Mode 1 observation without an inner breakwater. [d] Calculated, not observed. [e] "LST" denotes "Landing Ship Troops." [f] Predicted for shoals or inner breakwater. Mode 3 observed from the south leg of the inner breakwater to the harbor entrance. [g] In inner harbor. [h] Predicted for the north half of the inner harbor.

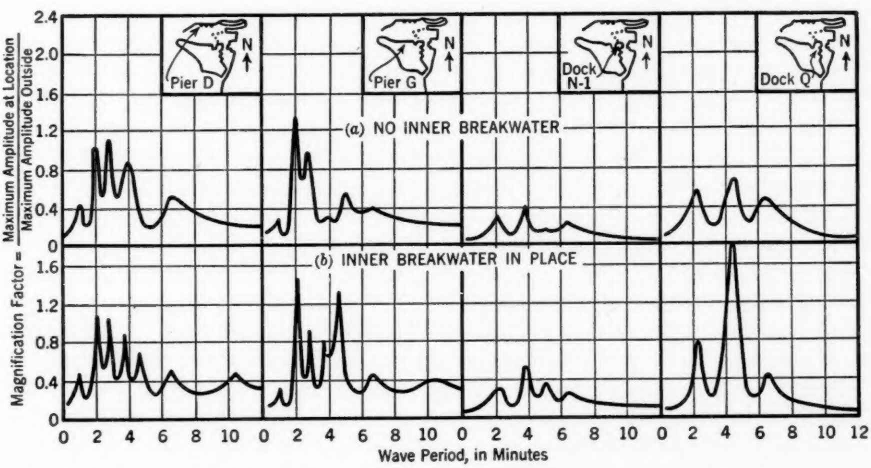


FIG. 8.—FREQUENCY RESPONSE ANALYSIS FOR REPRESENTATIVE LOCATIONS IN APRA HARBOR, GUAM

analysis took the form of measuring the vertical water motion as a function of incident wave period at a number of points in the harbor, most of which points were in operationally important docking areas, as shown in Fig. 8. An additional variation in this study was the determination of the effect of adding

a breakwater to an existing group of shoals that separate the outer harbor and repair basin.

Measurements of the horizontal water motion at resonant periods were obtained by photographing the movement of reflector floats drifting on the water surface. These observations assisted in the identification of modes of oscillation by defining nodal zones in which the horizontal motion is a maximum and permitted the determination of water velocities to be expected in the various docking areas as the result of a given surge condition.

The results of these studies indicate that Apra Harbor is subject to resonant oscillation, with amplification factors as high as two, for at least five surge periods in the range from 1 to 6 min. Horizontal water velocities as high as 0.25 knots per ft of imposed wave height may result in various docking areas as the result of such oscillations. The effect of adding a breakwater to the existing shoals is to increase their efficiency as a reflecting surface, especially for waves of longer than 3-min period, and to slightly restrict the excitation entering the repair basin and inner harbor areas.

Effects on Harbor Operations

Although the importance of long-period waves in harbors is entirely the result of the effect they may have on harbor operations, such as ship mooring and outfitting, this phase of the problem has been least studied. This deficiency did not come about because of lack of interest or misdirection of effort but because of the fact that, during World War II and during the immediate postwar period when funds for this necessarily expensive research were available, time was available only for the solution of the immediate problem of reducing the known bad excitation conditions. Since that time the level of activity has been greatly reduced because of the curtailment of funds. The only field observations available on which to base a few tentative conclusions are those made at Terminal Island, and the following discussion is limited to that extent.

Ship Mooring.—The most striking example of the importance of long-period waves or surges has been in connection with the mooring of ships to piers at the NOB. Even when restrained by very heavy tackle and sometimes even when the water surface appeared glassy, these moored ships have displayed longitudinal and transverse drift amplitudes of up to 10 ft, snapping mooring lines, breaking piles, and damaging the ships themselves.

The recorded experience at Terminal Island prior to the mole construction had shown the period of these damaging ship motions to be in the range from 2 to 3 min, corresponding to the observed ocean surge conditions. As a result of the model study, it was expected that 3-min surges would still be felt in the pier area but with lessened severity and that the most severe conditions within the mole could be expected with the arrival of 6-min period excitation. No persistent wave trains with periods in the 6-min range were recorded at Terminal Island until April 1, 1946. On this date a wave spectrum containing all periods from 1 min to 60 min, but with a large part of the energy contained in 6-min and 12-min period waves, arrived as the result of the Alaskan earthquake of that same date.

Records obtained from tide gages installed throughout the harbor, and, particularly in the NOB area, confirmed the predicted large amplitude water motions within the mole basin as a result of the 6-min excitation. Sufficient instruments were not available to map the motion of the water in the mole basin completely, but records from two significant stations—the pier area and the northwest corner of the basin—showed regular trains of 6-min waves with heights as great as 0.8 ft to 1 ft. The inference from these records is that the mole basin oscillated in the predicted mode with an amplification factor (ratio of maximum amplitude at location to maximum amplitude outside) of 1.5 or 2. However, an additional and surprising observation on this occasion was that, despite the relatively large amplitude, long-period water motion in the mole basin, no cases of unusual ship motion or damage were officially reported.

This evidence has led to the hypothesis that the motion of moored ships is a dynamic problem, with the possibility that a resonant period may exist that is a function of the mass of the ship and the elasticity of the mooring system. This theory offers a satisfactory explanation for the limited observed phenomena since approximate calculations show that the natural period of lateral oscillation of a typical ship-mooring line system is in the 2-min to 3-min range. Hence, it is in resonance with the usual type of long-period disturbances observed at Terminal Island and relatively unresponsive for either the 6-min or 15-sec excitation. In addition, it should be noted that the NOB was alerted for high waves from the Alaskan earthquake, and extra lines were added and moorings tightened on all ships. The effect of this precaution would be to stiffen the system and thus to reduce the natural period of oscillation, moving the resonant point even farther from the 6-min forcing period. The problem of the effect of ship mooring still is not settled but obviously warrants further investigation.

Ship Outfitting.—The problems peculiar to ship outfitting operations are a special case of shop mooring in which any appreciable motion is undesirable, even though it be much less than those that cause ship and pier damage. Thus, if heavy equipment must be hoisted from pier to ship and lowered accurately into position, either horizontal or vertical motions of fractions of a foot may be intolerable.

If, as seems clear from the Terminal Island study, the horizontal motion is the result of long-period waves and the vertical motion is the result of short-period waves, a theoretical solution would be to locate the outfitting dock at a point in the harbor where a node of the short-period standing wave pattern and a loop of the long-period standing wave pattern coincide. This combination would assure minimum values of horizontal and vertical water motion. At least part of this solution may be practical if the long-period excitation is fairly constant as to period, since the standing wave patterns are quite well defined for these long waves and may be determined analytically for simple harbors or may be determined for complicated harbors by model studies or field observations with suitable instruments.

Since the wave length of the standing wave pattern caused by the usual ocean waves is of the same order as the length of a ship, it is, of course, impossible to position the ship at a point of minimum vertical motion. However,

within a harbor there are always areas in which the ocean wave amplitudes are a minimum because of refractive and diffractive effects. By combining this fact with the previous observation of the practical possibilities of allowing for long-period standing waves, a rational choice of the quietest location in the harbor can be made.

Conclusions

The experience at Terminal Island has shown that the presence of long-period waves in harbors can constitute an important technical and economic problem. The possible extent of this problem is indicated by the fact that surge motion similar to that studied intensively at Terminal Island has been observed along the entire Pacific coast and at Hilo harbor in Hawaii. It is a fair assumption that these conditions exist in many parts of the world and go unreported, either because the lack of harbor developments prevent the occurrence of a problem or because many places that have a problem tolerate it through ignorance of possible remedial measures.

There are two fundamental aspects of this subject, on which additional information would be applicable to any particular problem. These are: (1) The cause and characteristics of long-period waves in the sea; and (2) the behavior of moored ships and other nonrigid structures under the influence of surge excitation. Future investigations of the harbor surge problem should certainly seek to expand the knowledge of these questions. Some particular suggestions for such a program are: (a) To test the theory of distant surf beat as a source of long-period waves by "hind casts"—determination of surf conditions from past meteorological records and subsequent refraction diagrams to project the long-period wave fronts from possible generating areas to areas in which long-period waves were observed; and (b) the accurate determination of the natural period of oscillation of moored ships by exact analytical methods or by experiment, using a large mechanical oscillator as the periodic driving force, as has been done for the determination of the critical periods of bridges and other large structures.

For any particular harbor, a model study is the best means to determine the location and magnitude of the standing wave patterns associated with any given excitation, permitting the design of harbor configurations to minimize surge motion and to accurately define optimum areas within the harbor for specified types of operational activity.

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